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LLNL Results from CALIBAN-PROSPERO Nuclear Accident Dosimetry Experiments in September 2014

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Table of Contents

Introduction	2
Objectives	2
Acknowledgements.....	2
Methods.....	3
Irradiation Setup	3
Measurements	7
Dose Calculations	10
Results.....	11
Discussion.....	13
Recommendations	16
Conclusions	16
References	17
Pending Presentation on Intercomparison Data	17
Appendix A. Figures with LLNL Specific PNAD Placement	18
Appendix B. Lawrence Livermore National Laboratory Nuclear Accident Dosimeter Data	24

Introduction

Lawrence Livermore National Laboratory (LLNL) uses thin neutron activation foils, sulfur, and threshold energy shielding to determine neutron component doses and the total dose from neutrons in the event of a nuclear criticality accident. The dosimeter also uses a DOE LAP accredited Panasonic UD-810 (Panasonic Industrial Devices Sales Company of America, 2 Riverfront Plaza, Newark, NJ 07102, U.S.A.) thermoluminescent dosimetry system (TLD) for determining the gamma component of the total dose. LLNL has participated in three international intercomparisons of nuclear accident dosimeters. In October 2009, LLNL participated in an exercise at the French Commissariat à l'énergie atomique et aux énergies alternatives (Alternative Energies and Atomic Energy Commission- CEA) Research Center at Valduc utilizing the SILENE reactor (Hickman, et.al. 2010). In September 2010, LLNL participated in a second intercomparison at CEA Valduc, this time with exposures at the CALIBAN reactor (Hickman et al. 2011). This paper discusses LLNL's results of a third intercomparison hosted by the French Institut de Radioprotection et de Sécurité Nucléaire (Institute for Radiation Protection and Nuclear Safety- IRSN) with exposures at two CEA Valduc reactors (CALIBAN and PROSPERO) in September 2014. Comparison results between the three participating facilities is presented elsewhere (Chevallier 2015; Duluc 2015).

Objectives

In 2014, LLNL was invited to IRSN to participate in a small-scale intercomparison. Participants included IRSN, Atomic Weapons Establishment (AWE - UK), and LLNL. The intercomparison provided a burst criticality experiment using the CALIBAN reactor and a steady state experiment using the PROSPERO reactor. LLNL tested the current Personnel Nuclear Accident Dosimeter (PNAD) design (Figure 1). The LLNL PNAD was originally developed in the early 1980's and evaluated in 1984 using neutron leakage spectra generated by the Health Physics Research Reactor at Oak Ridge National Laboratory (Hankins 1984). Fluence and dose conversion factors developed in 1984 have since been used for PNAD testing. However, some of these original factors have been adjusted to account for measurements and method changes. (Graham 2004).

The objectives of this exercise were:

- To test LLNL's PNAD with a pulsed neutron field and a steady state irradiation, as well as test the response at other orientations.
- To compare PNAD results with IRSN and AWE.
- Determine areas of needed improvement.
- To train LLNL employees on neutron accident dosimetry and
- To strengthen collaborations with IRSN and AWE.

Acknowledgements

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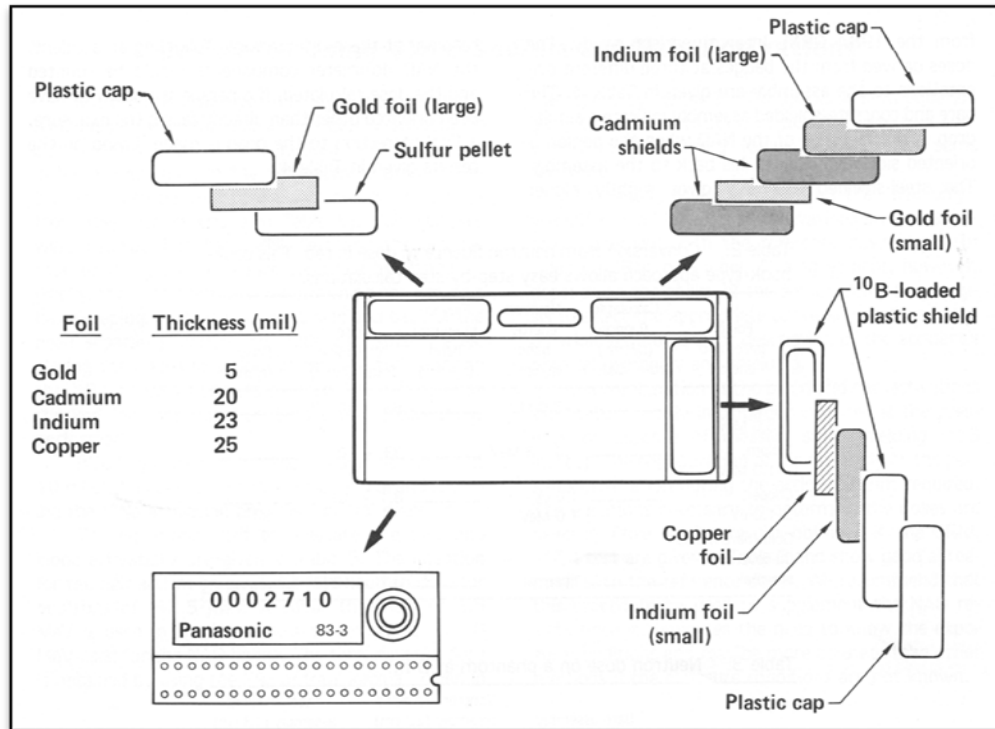


Figure 1. Lawrence Livermore National Laboratory Personnel Nuclear Accident Dosimeter design.

Methods

The theoretical basis and computational methods for LLNL's Nuclear Accident Dosimetry program were published previously (Hankins 1984, Hankins 1988, Graham 2004, Hickman, et.al. 2010). LLNL maintains a Technical Basis Document (TBD) that describes the methods and computations used for the LLNL PNAD.

Irradiation Setup

Two irradiations were performed during the week of September 1, 2014. The burst experiment was performed using CALIBAN on September 2, 2014 at 12:25 hrs (GMT+1). The steady state experiment was performed using PROSPERO on September 3, 2014 starting at 11:39 hrs (GMT+1) and lasting 1500s. After each irradiation at CEA Valduc, the dosimeters were transported by IRSN personnel to the Fontenay-aux-Roses facility, near Paris, approximately 3.5 hours away. The dosimeters arrived for measurement between 6 and 7 hours post irradiation.

For each irradiation, there were four arrangements for the dosimeters: (1) placed on a phantom facing the core at a 0° orientation, (2) placed on a stand in free air facing the core at a 0° orientation, (3) on a phantom facing the core with a 45° orientation, or (4) on the back of a phantom facing the core with a 45° orientation (effectively a 225° orientation). The height and dosimeter placement on the stand, when possible, mimicked the height and dosimeter placement for the phantom with the same orientation. The phantom was an 80cm tall elliptical plastic cylinder filled with sodium water. Phantoms were placed on

aluminum stands to achieve a total height of approximately 160cm. Plastic sheets draped over top of the phantom with pockets were used to arrange the dosimeters (see pictures in Appendix A). The location of each dosimeter on phantom differed slightly depending on the pocket in which the dosimeter was placed, but the effect of the specific location on the phantom versus dosimeter response wasn't considered.

CALIBAN

Nine PNADs and 1 set of Personnel Ion Chambers (PIC) were placed on the core facing phantom (P_3), 9 PNADs and 1 set of PIC on the core facing stand (S1), 3 PNADs on the front of the phantom at a 45° angle (P_2) with the left side of the phantom forward, and 3 PNADs on the rear of the phantom at a 45° angle (P_2). All dosimeters were situated at 3m from the core (Figure 2 and Figure 3). Each set of PIC contained 4 individual chambers, each with a different maximum scale: 0-20R; 0-100R; 0-200R; and 0-600R. Figure 9 through Figure 11 in Appendix B gives specific LLNL PNAD placement for the CALIBAN irradiation.

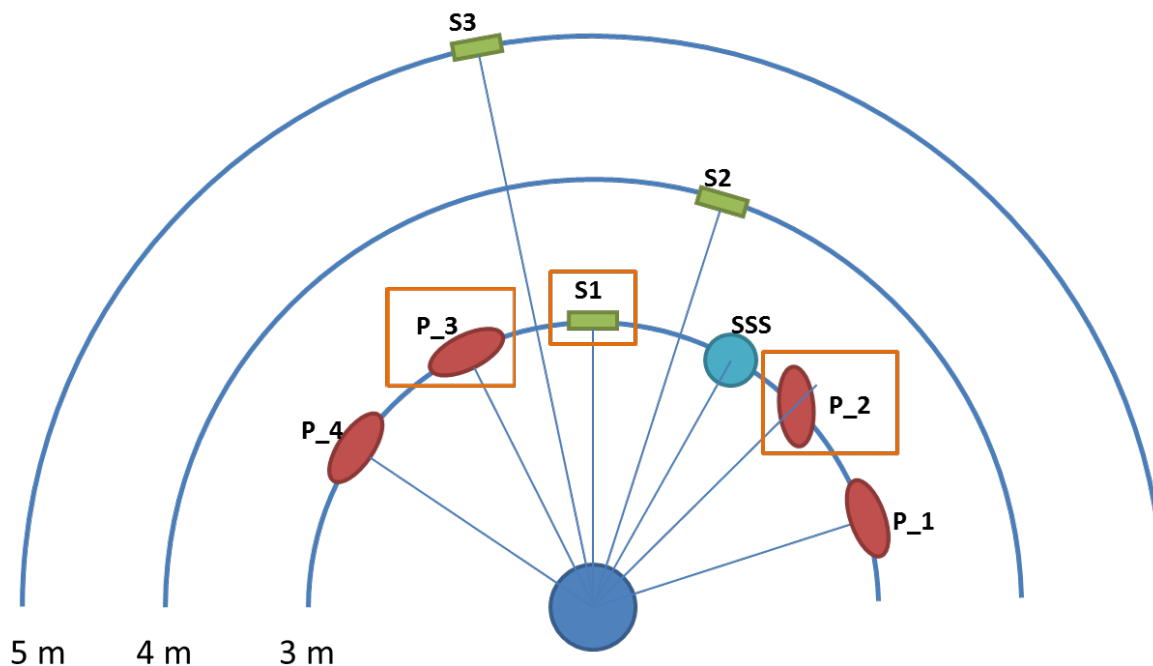


Figure 2. Irradiation positions for the exposure at the CALIBAN reactor (Courtesy of IRSN). The orange squares indicate locations where LLNL PNADs were placed. The red ovals represent phantoms and the green rectangles represent aluminum stands in free air.

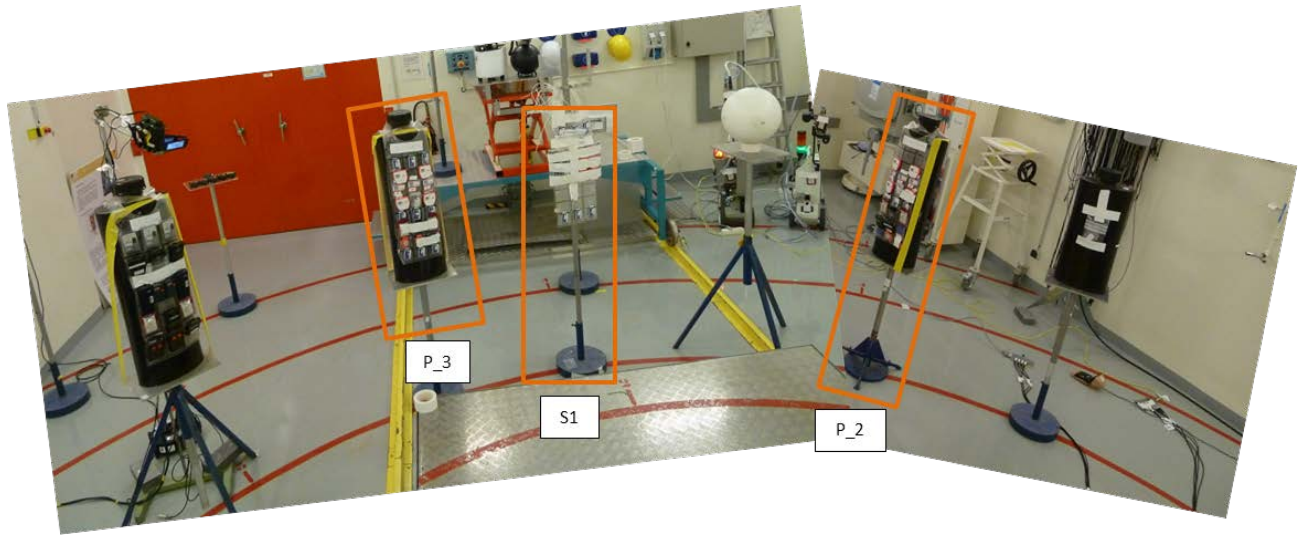


Figure 3. Photographs of the CALIBAN Irradiation Setup drawn in Figure 2. Orange boxes indicate phantoms and the stand holding LLNL PNADs. Photographs courtesy of IRSN.

PROSPERO

The setup for the PROSPERO steady state irradiation consisted of 4 configurations: (1) 6 PNADs and 1 set of PIC on the front of a core facing phantom (P_5), (2) 6 PNADs and 1 set of PIC on the front of a core facing stand (S4), (3) 3 PNADs on the front of a phantom at an angle of 45° (P_6), and (4) 2 PNADs on the rear of a phantom at an angle of 45° (P_6). All dosimeters were situated at 3.5m from the core (Figure 4 and Figure 5). Each set of PIC contained 4 individual chambers, each with a different maximum scale: 0-20R; 0-100R; 0-200R; and 0-600R. Figure 12 through Figure 14 in Appendix B gives specific LLNL PNAD placement for the PROSPERO irradiation.

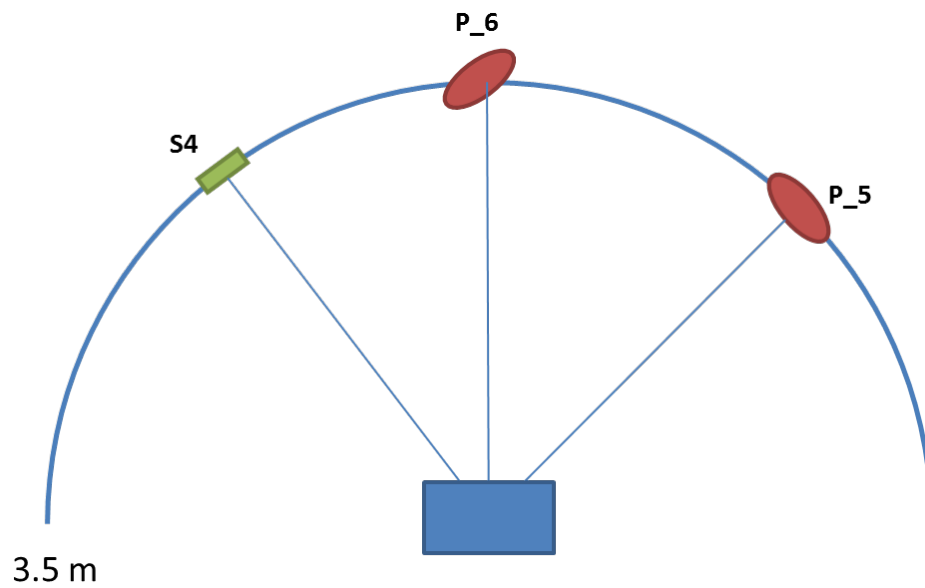


Figure 4. Drawing of irradiation setup for the PNAD exposure at the PROSPERO reactor (Courtesy of IRSN). LLNL had PNADs at each location represented. Similar to Figure 2, the red ovals represent phantoms and the green rectangles represent a stand in free air.

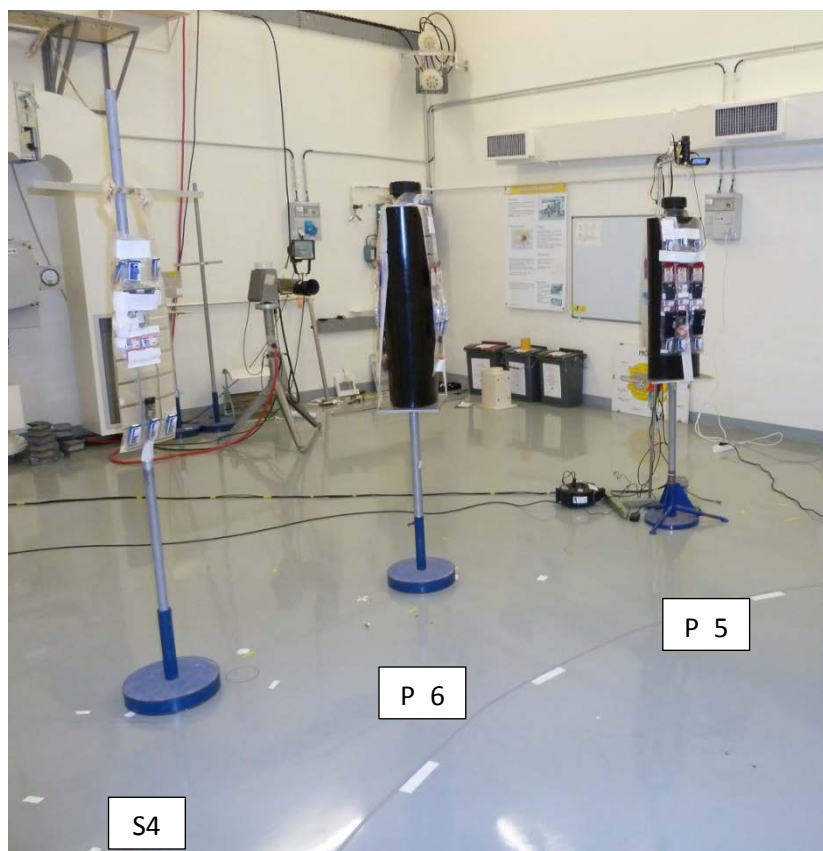


Figure 5. Photograph of the PROSPERO irradiation setup drawn in Figure 4. Photographs courtesy of IRSN.

Measurements

The activation foils and sulfur pellets are separated from the TLD housing and placed in a labeled glassine envelope for counting. The individual foils are measured using an electrically cooled high purity germanium (HPGe) detector. The LLNL detector was efficiency calibrated using the mathematical calibration software ISOCS (Canberra Industries, Inc., 800 Research Parkway, Meriden, CT 06450, U.S.A.), assuming the typical measurement geometry and average foil dimensions (Table 1). For measurements on the LLNL system, each foil is centered on the face of the detector (Figure 6). Due to technical difficulties with the LLNL detector system while in France, some foils were measured on the same model detector owned by AWE. The measurement geometry on the AWE system was slightly different than the LLNL measurement geometry (Figure 7). While the effect of this change of geometry on measurement efficiency was determined to be negligible, the ease of performing calibrations with ISOCS allowed for geometry-specific modeling of the alternative measurement geometry. Foil measurement times were adjusted based on the available time for counting and expected activity of the foils; the desired number of counts in each ROI is given in Table 1. Daily quality control measurements for energy and efficiency calibration were made using a thorium mantle.

The irradiated sulfur pellets were measured whole using an iSolo alpha/beta counter (Canberra Industries, Inc., 800 Research Parkway, Meriden, CT 06450, U.S.A.). The iSolo was calibrated with a 50

mm distributed Sr/Y-90 source close to the detector. Sample count times were set to twenty minutes. Background measurements were typically counted for 20 or 30 minutes and performed at least every 10 sample counts. Daily calibration checks were performed using a thorium mantle containing natural beta emitting radionuclides.

The Panasonic TLDs were measured upon returning to Livermore using DOELAP accredited LLNL External Dosimetry procedures. The PICs were read upon receipt in France by two individuals to confirm the exposure readings.

Table 1. Average dimensions of the PNAD foils used for the efficiency calibration of the HPGe detector.

Foil Type	Weight (g)	Length (mm)	Width (mm)	Thickness (mm)	Measurement Nuclide	Photon Energy Emission (keV)	Desired Counts in the ROI
Small Indium	0.363	19.13	4.66	0.62	^{115m} In	336	2000
Copper	0.346	16.34	3.75	0.65	⁶³ Cu	511	500
Small Gold	0.222	17.94	4.57	0.15	¹⁹⁷ Au	411	2000
Large Gold	0.292	20.67	6.05	0.15			



Figure 6. Photograph of the LLNL portable counting system set-up; sample is centered on the face of the detector.

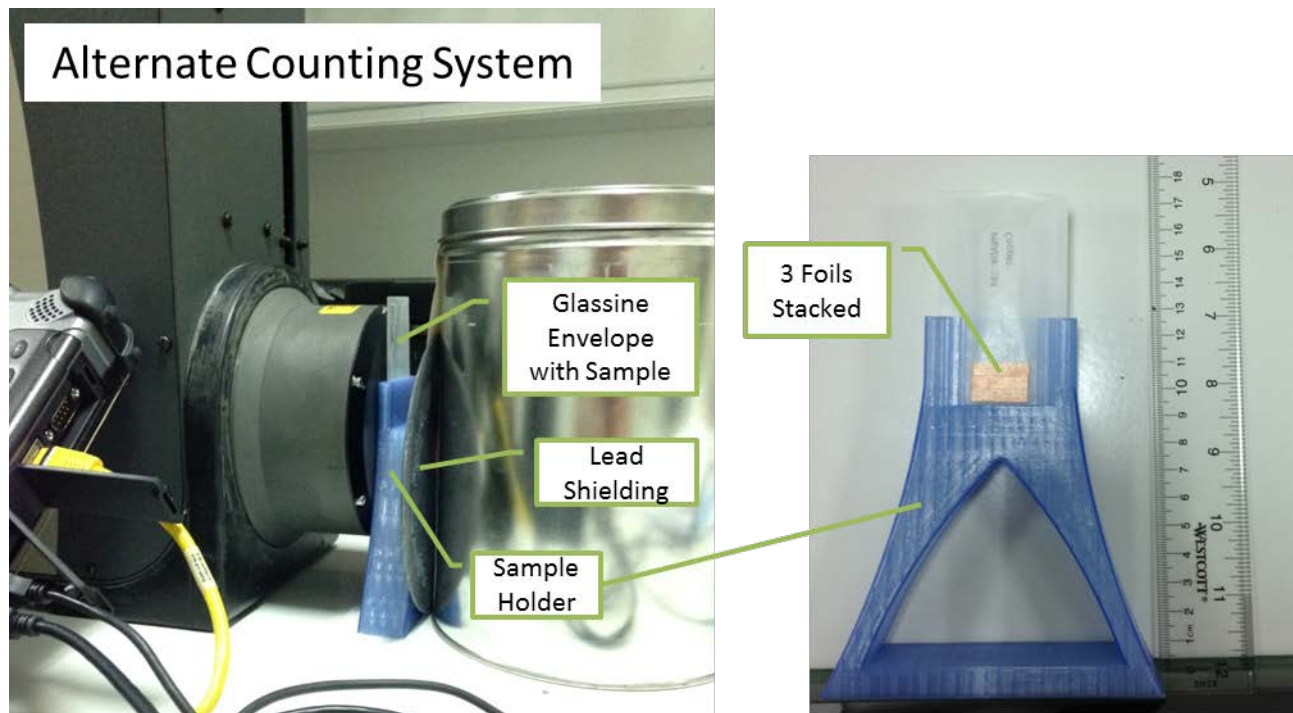


Figure 7. Photograph of the AWE counting system setup. Center of the three stacked foils is approximately 10cm from the tabletop.

Dose Calculations

Neutron dose was measured using the activity results of the activation elements in the LLNL PNAD and gamma dose was measured using the Panasonic UD-810 thermoluminescent dosimeter and confirmed with PIC readings. These measured dose values were compared to the reference neutron KERMA and reference photon dose at 10cm provided by IRSN.

Neutron Dose Calculations

Decay-corrected activity concentrations ($\mu\text{Ci/g}$) (corrected to the time of irradiation) were used to determine the neutron fluence (n/cm^2) for the energy range represented by each activation component of the PNAD. The LLNL neutron fluence to dose conversion factors used for PNAD dose calculation were empirically determined and discussed elsewhere (Hankins 1984). The neutron fluence to tissue KERMA conversion factors used for these calculations were empirically determined from experiments at the National Criticality Experiments Research Center (NCERC) in 2014. Table 2 lists the conversion factors used for the results discussed in this paper.

For the steady state irradiation at PROSPERO, the neutron fluence is adjusted for the activation build-up using:

$$\frac{t \times \lambda}{1 - e^{-\lambda t}}$$

where t is the irradiation time and λ is the decay constant associated with the measured foil. Correction factors were previously developed for exposures at 90° and 180° orientation (Hankins 1984), but not the

45° angular exposure. For preliminary analysis, a ‘best estimate’ neutron correction factor of 0.73 was interpolated from the Hankins (1984) data for the 45° orientation with dosimeters on the front of the phantom. A neutron correction factor for the dosimeters on the back of the 45° oriented phantom, or at an angle of 225°, was not determined and could not be evaluated.

Table 2. Conversion factors used for dose calculation from the NAD measurement results.

NAD Element	Approximate Neutron Energy Range	Activity to Fluence Conversion Factor (n g cm ⁻² uCi ⁻¹)	Fluence Steady State Irradiation Factor	Fluence to Dose Conversion Factor (rads cm ² n ⁻¹)	Fluence to KERMA Conversion Factor (rad cm ² n ⁻¹)
Shielded In	1 - 3 MeV	6.81x10 ¹¹	1.03	3.3x10 ⁻⁹	2.79x10 ⁻⁹
Sulfur	> 3 MeV	2.90x10 ¹³	1.00	5.3x10 ⁻⁹	4.14x10 ⁻⁹
Copper	1 eV - 1 MeV	5.01x10 ¹²	1.01	8.1x10 ⁻¹⁰	8.37x10 ⁻¹⁰
Gold	Thermal	3.00x10 ¹⁰	1.00	7.0x10 ⁻¹¹	1.15x10 ⁻¹¹
Shielded Gold	----	3.00x10 ¹⁰	1.00	----	----

Gamma Dose Calculations

Gamma dose was determined by two methods for this exercise: (1) the Panasonic 810 TLD included in each PNAD and (2) by PIC. The gamma dose determined using the TLD was calculated using the established procedures and algorithms employed in the LLNL external dosimetry program (Topper 2010). No orientation correction factor was applied for gamma measurements at the 45° angle.

Results

For each irradiation configuration, the arithmetic mean of the multiple dosimeters located in that configuration is quoted as the average. For neutron doses, the propagated measurement uncertainty is quoted as the 1 σ uncertainty, unless otherwise noted. For the gamma doses, the standard deviation of the TLD readings is quoted as the 1 σ uncertainty. Detailed dose and neutron fluence calculation results are provided in Appendix B.

Table 3 provides a summary of the core-facing (0° orientation) average neutron tissue KERMA with a comparison to the reference KERMA for both irradiations. Table 4 provides a summary of the average neutron tissue KERMA results for dosimeters situated on the phantom at a 45° angle and a comparison to the reference KERMA for the irradiation; the average measured LLNL neutron KERMA represents the standard calculation, while LLNL neutron KERMA with Orientation Factor represents the standard calculation adjusted using the interpolated orientation factor. Table 5 provides average gamma dose results determined from the PICs and the TLD; Table 6 provides the total dose, defined for this experiment as the sum of neutron KERMA and the gamma dose. Figure 8 displays the contribution to total neutron dose from each neutron energy range measured by the activation elements in the LLNL PNAD.

Table 3. Neutron KERMA results summary for core-facing PNAD (0° orientation) with 1σ standard deviation.

Irradiation	Location	Distance (m)	Reference Neutron KERMA (Gy)	Average LLNL Neutron KERMA (Gy)	Percent Difference
Burst CALIBAN	Phantom	3	1.17	1.14 ± 0.03	-3%
Burst CALIBAN	Stand	3		1.08 ± 0.05	-8%
Steady State PROSPERO	Phantom	3.5	0.12	0.13 ± 0.00	8%
Steady State PROSPERO	Stand	3.5		0.13 ± 0.01	8%

Table 4. Best estimate neutron KERMA results summary for PNADs situated on the phantom with a 45° orientation. The fifth column represents the average measured neutron KERMA and the seventh column represents the neutron KERMA after adjustment with correction factor based on previous orientation studies using a linear interpolation (Hankins 1984).

Irradiation	Location	Distance (m)	Reference Neutron KERMA (Gy)	Average Measured LLNL Neutron KERMA (Gy)	Percent Difference	LLNL Neutron KERMA with Orientation Factor	Percent Difference
Burst CALIBAN	Front	3	1.17	1.07 ± 0.04	-9%	1.46	25%
Burst CALIBAN	Rear	3		0.55 ± 0.04	-53%	-	-
Steady State PROSPERO	Front	3.5	0.12	0.15 ± 0.00 ^A	25%	0.20	67%
Steady State PROSPERO	Rear	3.5		0.16 ± 0.02 ^A	33%	-	-

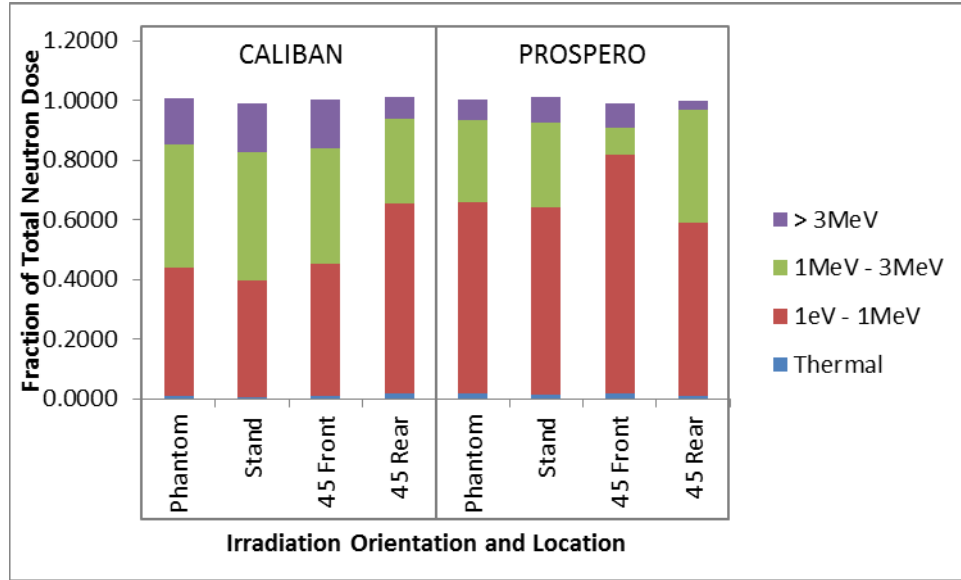
^A These results were determined from only one measurement of all the foils at that location; uncertainty is the propagated 1σ measurement uncertainty.

Table 5. Gamma dose results summary including both the TLD and PIC measurements. No orientation factors were applied to gamma dose measurements for the dosimeters at 45° angle.

Irradiation	Location	Orientation	Distance (m)	Reference Gamma Dose (Sv)	Average LLNL PIC Gamma Dose (Sv)	Average LLNL TLD Gamma Dose (Sv)	Percent Difference
Burst CALIBAN	Phantom	0°	3	0.22	0.58	0.69 ± 0.12	214%
Burst CALIBAN	Stand	0°	3		0.56	0.46 ± 0.08	109%
Burst CALIBAN	Phantom Front	45°	3		-	0.68 ± 0.07	209%
Burst CALIBAN	Phantom Front	45°	3		-	0.53 ± 0.07	141%
Steady State PROSPERO	Phantom	0°	3.5	0.03	0.11	0.10 ± 0.03	233%
Steady State PROSPERO	Stand	0°	3.5		0.10	0.06 ± 0.01	100%
Steady State PROSPERO	Phantom Front	45°	3.5		-	0.11 ± 0.04	267%
Steady State PROSPERO	Phantom Front	45°	3.5		-	0.06 ± 0.00	100%

Table 6. Total dose (neutron KERMA + gamma dose) for core-facing configurations.

Irradiation	Location	Distance (m)	Reference Total Dose (Gy)	LLNL Total Dose (Gy)	ANSI 13.3-2013 Performance Statistic (B)	Meets ANSI 13.3 Requirements?
Burst CALIBAN	Phantom	3	1.39	1.83	31%	NO, >25%
Burst CALIBAN	Stand	3		1.54	11%	YES
Steady State PROSPERO	Phantom	3.5	0.15	0.25	68%	NO, >50%
Steady State PROSPERO	Stand	3.5		0.22	46%	YES

**Figure 8.** Contribution to total neutron dose from each neutron energy range for all irradiation configurations.

Discussion

The LLNL PNAD performed extremely well for estimating neutron doses. The neutron KERMA results for the core-facing dosimeters were within 8% of the reference value (Table 3). During the experiments, the LLNL gamma detection equipment became inoperable for over 12 hours. To make up for the loss of counting time, the measurement times were adjusted and some foils were measured on the AWE equipment. Given the adjustments to procedure and counting protocols, the accuracy of these experimental results are very encouraging and support the current LLNL protocols and contingency actions in the event of an actual criticality event where adjustments and use of various counting systems may be required.

LLNL has never evaluated dose correction factors for dosimeters situated at 45° to a simulated criticality accident. The dosimeters on the front of the 45° phantom provided tissue KERMA doses within 25% of the reference value without correction for angular orientation (Table 4). The dosimeters on the back of the 45° phantom had greater neutron attenuation than dosimeters on the front. The 45° phantom

results were not compared between the facilities, but do provide LLNL with data, albeit limited, regarding the effect of orientation and phantom attenuation on the PNAD response. Angular orientation of the dosimeters is one aspect of the LLNL nuclear accident dosimetry program requiring additional evaluation and development. Angular correction factors for 90° and 180° are given in the Hankins 1984 report, but the exact configuration isn't provided (left or right side towards the core). The 2010 experiments had dosimeters placed in the sideways orientation (90°) with both the right and left side facing the core to test differences between left and right side orientations, as well as confirm the correction factors, but results were inconclusive (Hickman 2011). The current experiments had only 11 dosimeters configured at the 45° angle, with 6 on the front of the phantom (45°) and 5 on the back of the phantom (225°). These results would not provide enough data to determine an empirical-adjustment factor to account for the 45° and 225° orientation. Using the interpolated correction factor did not provide a better estimate of the reference dose; the percent difference in both cases increased after application of the correction factor (Table 4). The limited data for the dosimeters on the front of the phantom oriented at 45 degrees suggest that a correction factor isn't required to meet the ANSI testing guidelines, however for dosimeters positioned on the back of the 45 degree oriented phantom the results indicate that additional study is needed. Further studies on the orientation of the dosimeter and body are needed to establish the relative correction factors for orientations not previously measured. Future work, both experimental and simulated modeling, is needed to provide more specific and additional angular orientation correction factors, as well as confirm the current correction factors. An additional aspect of orientation, which should be investigated, is the potential for the PNAD response itself to provide an indication of the dosimeter orientation.

The accuracy and consistency of the gamma dose results from simulated criticality events have previously been recognized as an area for improvement (Hickman 2010). Incorporated originally in the 2010 intercomparison, one change which improved LLNL gamma doses in previous intercomparisons was the use of PICs to supplement the TLD measurements. In this intercomparison, the LLNL PNAD (Panasonic TLD UD-810) and PICs both overestimated the gamma dose by about a factor of 2-3, but were in good agreement with each other. One theory as to why the TLD overestimated the gamma dose has been proposed and needs additional investigation, but currently it is not known why the TLD and PIC measurements would be in agreement given this theory.

The Panasonic UD-810 dosimeter is composed of 4 phosphor elements to measure dose: (E1) ${}^7\text{Li}_2{}^{11}\text{B}_4\text{O}_7$ with 14 mg/cm² of plastic as filtration, (E2) ${}^7\text{Li}_2{}^{11}\text{B}_4\text{O}_7$ with 510 mg/cm² of plastic as filtration, (E3) ${}^6\text{Li}_2{}^{10}\text{B}_4\text{O}_7$ with 560 mg/cm² of plastic and aluminum as filtration, and (E4) CaSO with 510 mg/cm². The theoretical design basis for this dosimeter is: E1 measures gammas and betas, E2 measures gammas, E3 measures slow neutrons and gammas, and E4 measures gammas. E1 and E2 are theoretically not sensitive to slow neutrons; the slow neutron cross-sections for ${}^7\text{Li}$ and ${}^{11}\text{B}$ are very low ($\ll 1$ barn). Though E1 and E2 are composed mainly of the low neutron capture cross-section isotopes of lithium and boron, there is a probability of having small quantities of ${}^6\text{Li}$ and/or ${}^{10}\text{B}$ 'contamination' with the other natural isotopes due to imperfections in the LiBO enrichment process. Natural lithium is composed of approximately 7.5% ${}^6\text{Li}$ and 92.5% ${}^7\text{Li}$; natural boron is composed of approximately 19.9% ${}^{10}\text{B}$ and 80.1% ${}^{11}\text{B}$. The presence of even minute quantities of ${}^6\text{Li}$ or ${}^{10}\text{B}$ in ostensibly pure ${}^7\text{Li}_2{}^{11}\text{B}_4\text{O}_7$ neutron-insensitive

phosphors could easily skew the resulting data in the event of high KERMA neutron exposures. Unfortunately, Panasonic doesn't provide quality control specifications or tolerance limits for the amount of ^6Li or ^{10}B in the $^7\text{Li}^{11}\text{B}$ enriched phosphor elements.

Additional simulations and experiments will be required to confirm the extent to which isotope contamination of TLD elements is contributing to the gamma dose overestimation and to help in determining the appropriate actions moving forward. A potential solution to decrease the effect of neutron interactions within the phosphors on the gamma dose calculation is to develop a new neutron accident algorithm. The E4 reading could be used alone to determine the gamma dose up to a certain dose threshold and above that threshold the E2 reading with an empirically-derived adjustment factor ($E4/E2$), to account for the neutron interaction-induced signal, could be used to determine the gamma dose. E4, the CaSO element, is insensitive to neutrons, but at high doses the light output saturates the TLD reader, therefore the E2 reading would be required for photon doses greater than approximately 100 rem, photon. The adjustment factor ($E4/E2$) suggested by this data is approximately 1.7. This adjustment factor should not be accepted and used until additional testing confirms this theory and the value. Applying the suggested solution to this data set, the CALIBAN gamma doses determined using the E4 reading for all results were within 45% of the reference gamma dose values (Table 7). Total doses (Neutron KERMA + gamma dose) measured by the LLNL PNAD were well within the ANSI 13.3-2013 requirements of $\pm 25\%$ for doses within 1-10 Gy (CALIBAN) and $\pm 50\%$ for doses within 0.1-1 Gy (PROSPERO).

One drawback to the suggested method for adjusting the criticality accident photon doses is determination of the empirically-derived adjustment factor. This factor would only be used for photon doses greater than 100 rem, but would rely heavily on tight quality control specifications for production of the phosphors. The adjustment factor would be dependent on the amount of contamination in the phosphor and without knowing the quality control specifications for the allowable amount of ^6Li and ^{10}B in the $^7\text{Li}^{11}\text{BO}$ phosphors, the empirically-derived adjustment factor may not apply to new dosimeters or to all dosimeters currently in the LLNL dosimeter population. At the current time, the manufacturer doesn't provide this information. Therefore, extensive testing would be required to confirm similarity with the dosimeters used to empirically-derive this adjustment factor.

Despite the overestimation of the gamma dose and the PNAD gamma detection system malfunction, the total dose results for PNADs on the stand are well within the ANSI N13.3-2013 performance testing criteria (Table 6). The LLNL procedure for measuring and analyzing the PNAD for nuclear accident doses has a long history with many experimental results validating the robustness and accuracy of the method. This intercomparison again demonstrated successful outcomes in a field-based operation and under non-normal circumstances, as well as the value of LLNL collaborations with AWE and IRSN. These experiments were the last irradiations to be performed before the closure of the CALIBAN and PROSPERO reactors, highlighting the importance of the NCERC facility at NNSS and the need to maintain the experimental capability it provides.

Table 7. Gamma doses calculated from the TLD data by applying the suggested solution to avoid neutron interaction-induced signal in the gamma dose phosphors.

Irradiation	Location	Orientation	Distance (m)	Reference Gamma Dose (Sv)	Dose applying the Proposed Solution (Sv)	Percent Difference
Burst CALIBAN	Phantom	0°	3	0.22	0.32 ± 0.02	45%
Burst CALIBAN	Stand	0°	3		0.22 ± 0.02	0%
Steady State PROSPERO	Phantom	0°	3.5	0.03	0.04 ± 0.00	33%
Steady State PROSPERO	Stand	0°	3.5		0.03 ± 0.00	0%

Recommendations

- Perform simulations and experiments at NCERC to determine a more appropriate nuclear accident algorithm for gamma dose calculation via TLD, either using the neutron insensitive element (CaSO) reading or adjusting the LiBO element reading with an empirical correction factor, and incorporate this new algorithm into the external dosimetry analysis routine.
- Test additional angular orientations using the facilities at NCERC and computer simulations to aid in determining whether it is appropriate to incorporate a dose correction factor for PNAD/personnel orientation.
- Based on the experiences at the IRSN and this exercise the LLNL Team established a set of recommendations to improve the success of upcoming intercomparisons at the NCERC laboratories:
 - Recommendations for the NCERC facility improvements include: additional work and measurement space, rolling tables for configurable work spaces, and uninterrupted power supplies and power conditioners to prevent electrical disruptions.
 - Recommendations for the LLNL measurement process include: establishing a more robust spectral analysis routine which can be applied to multiple gamma spectrometers regardless of energy calibration differences, assure adequate sets of batteries for Falcon gamma systems so power outages have minimal effect on continued operations.

Conclusions

This exercise provided a great opportunity to train new personnel on nuclear criticality accident dosimetry, as well as to strengthen collaborations with AWE and IRSN. These were the last experiments performed on the CALIBAN and PROSPERO reactors before their decommissioning, which highlights the importance of the NCERC facility at NNSS and the need to maintain the experimental capability it provides. Total dose results for the phantom configurations were outside the acceptable ANSI N13.3-2013 performance testing criteria due to the overestimation of the gamma dose, but research and improvements to the gamma dose calculations should bring total doses into compliance with ANSI requirements. Total dose results for the stand configuration were within the ANSI N13.3-2013

performance testing criteria. Future work and proposed improvements to the LLNL PNAD process were identified, but overall the LLNL PNAD responded very well for evaluating neutron doses.

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Pending Presentation on Intercomparison Data

- Duluc M, et al. "2014 CALIBAN and PROSPERO Experiments for the Criticality Accident Dosimetry Intercomparison." International Conference on Nuclear Criticality Safety. Charlotte, NC: American Nuclear Society; September 13-17, 2015.

Appendix A. Figures with LLNL Specific PNAD Placement

All photographs are courtesy of IRSN.



NAD 535	NAD 539	NAD 541
IRSN	-	IRSN
IRSN	IRSN	IRSN
IRSN	IRSN	IRSN
NAD 543	NAD 544	NAD 546
IRSN	AWE	IRSN
AWE	AWE	AWE
NAD 547	NAD 548	NAD 549

Figure 9. Photograph of phantom P_3, which was situated at 3m with 0° orientation for the CALIBAN exposure and corresponding LLNL PNAD identification.



NAD 550	-	NAD 551	-	NAD 552
-	-	-	-	-
NAD 553	NAD 554	NAD 555	IRSN	IRSN
LLNL-11 PIC			IRSN	IRSN
			IRSN	IRSN
-	-	-	-	-
NAD 556	-	NAD 557	-	NAD 558

Figure 10. Photograph of stand S1, situated at 3m with 0° orientation for the CALIBAN irradiation and corresponding LLNL PNAD identification.

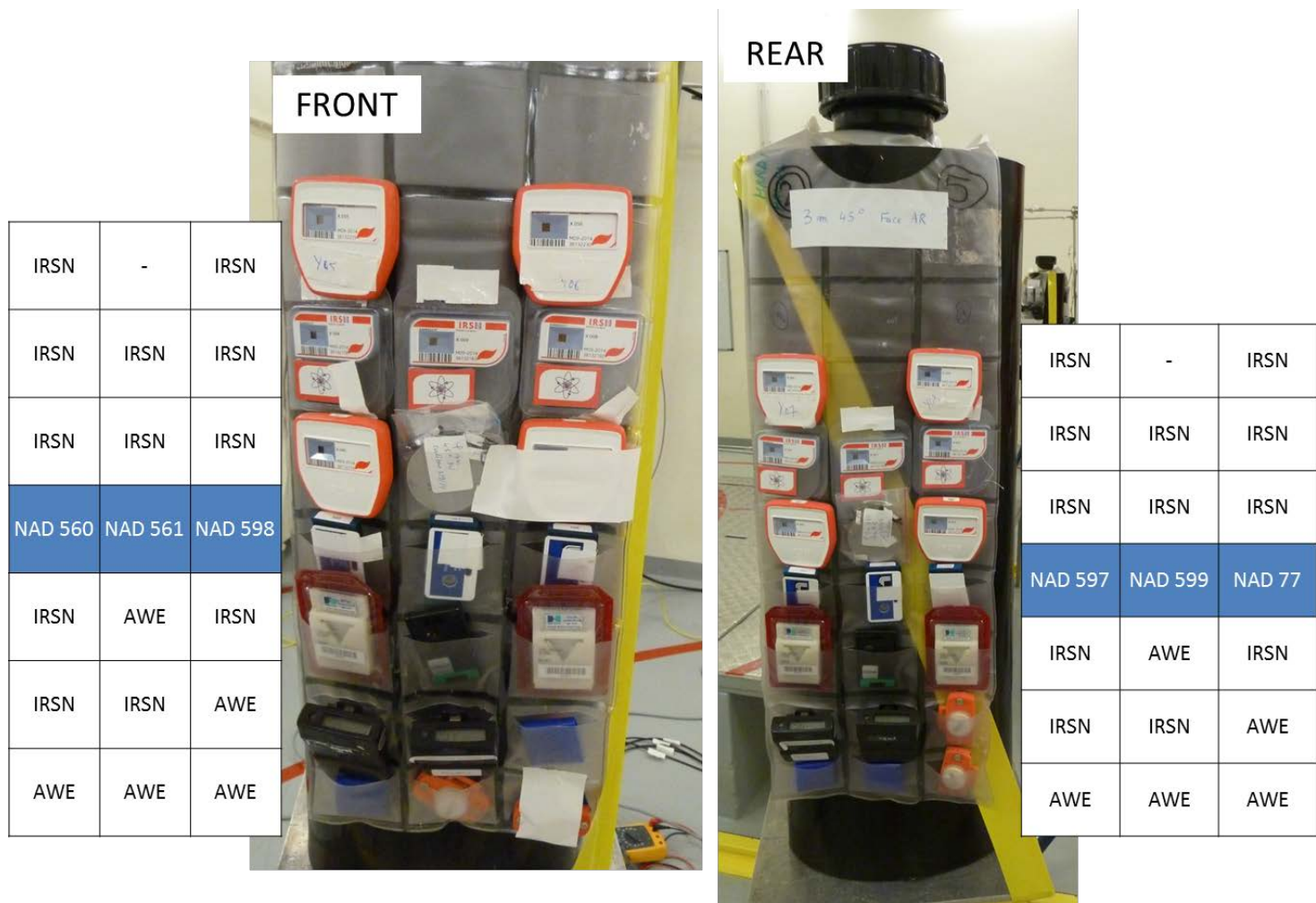


Figure 11. Photographs of the phantom P_2, situated at 3m from the core with a 45° orientation for the CALIBAN exposure and corresponding LLNL PNAD identification.



NAD 562	NAD 563	NAD 565
-	PIC LLNL-12	-
IRS	IRS	IRS
IRS	IRS	IRS
IRS	IRS	IRS
IRS	AWE	IRS
-	AWE	-
NAD 566	NAD 568	NAD 570

Figure 12. Photograph of Phantom P_5 setup for the PROSPERO irradiation, situated at 3.5m with 0° orientation, and the corresponding LLNL PNAD identification.

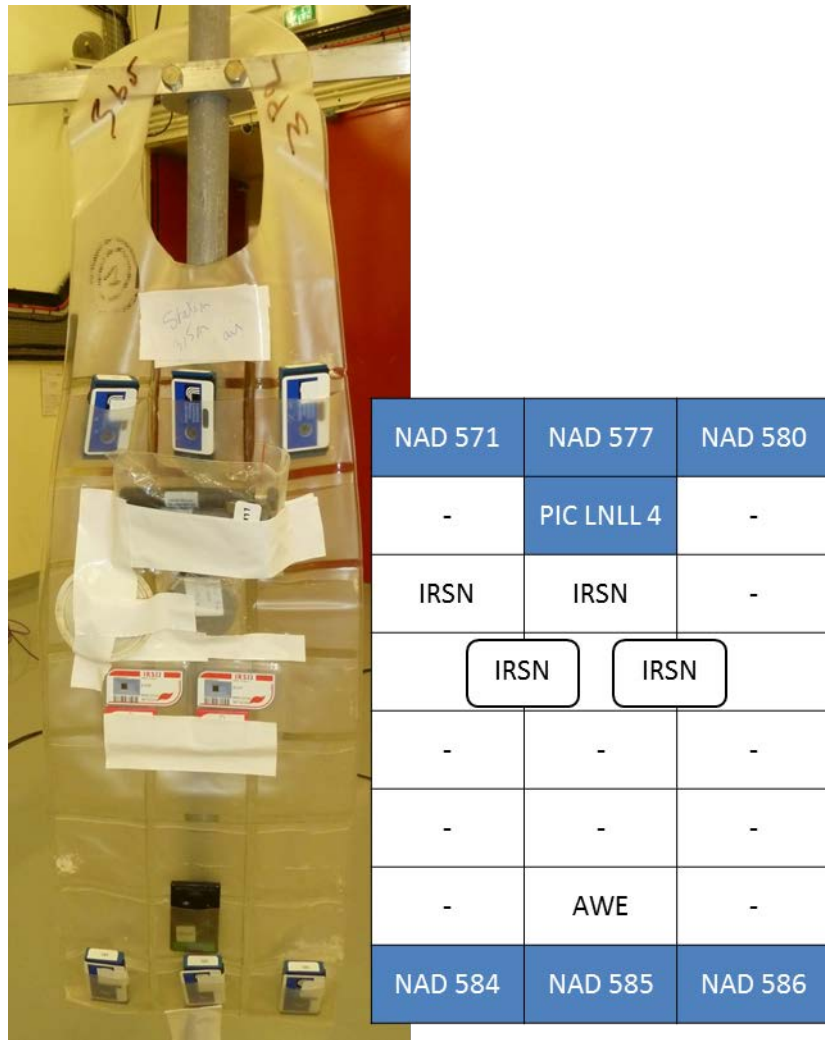


Figure 13. Photograph of Stand S4 setup for the PROSPERO irradiation, situated at 3.5m with 0° orientation, and the corresponding PNAD identification.

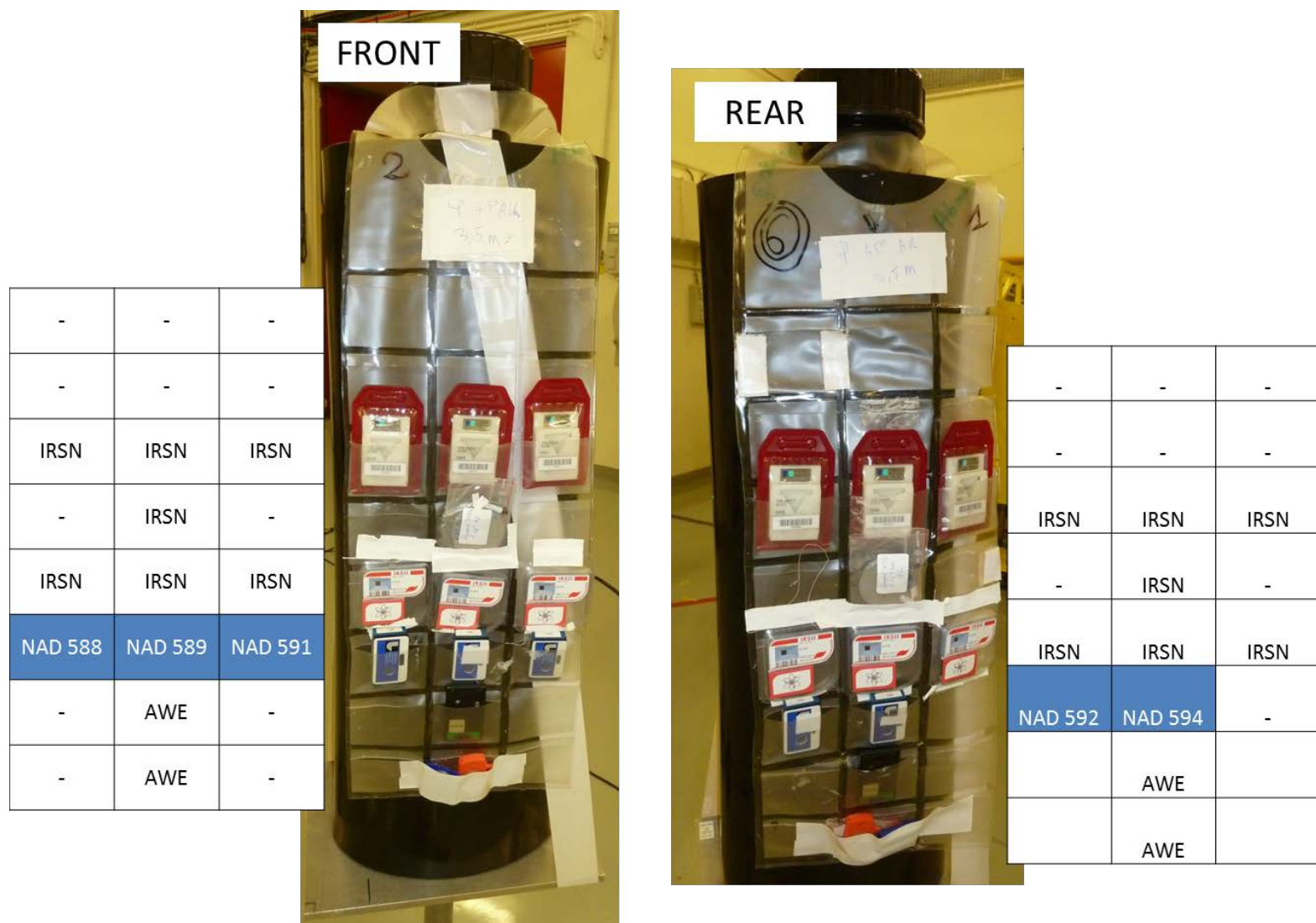


Figure 14. Photograph of phantom P_6 setup for the PROSPERO irradiation, situated at 3.5m with a 45° orientation, and the corresponding LLNL specific PNAD identification.

Appendix B. Lawrence Livermore National Laboratory Nuclear Accident Dosimeter Data

Table B1. PNAD location, masses of the activation elements, and identification information.

PNAD ID	Irradiation	Location	Distance (m)	Height (cm)	Position	B Covered In Mass (g)	S Mass (g)	Cu Mass (g)	Bare Au Mass (g)	Cd Covered Au Mass (g)	CR-39 TASL #	Panasonic TLD ID
535	Caliban 3	Phantom (P_3)	3	161	Top	0.3688	0.8821	0.4625	0.2705	0.2103	1302447	0006247
539	Caliban 3	Phantom (P_3)	3	161	Top	0.3820	0.8408	0.4629	0.2914	0.2123	1302476	0010280
541	Caliban 3	Phantom (P_3)	3	161	Top	0.3621	0.8609	0.4624	0.2764	0.2138	1302440	0030242
543	Caliban 3	Phantom (P_3)	3	161	Middle	0.3666	0.8588	0.4809	0.2865	0.2094	1302444	0004079
544	Caliban 3	Phantom (P_3)	3	161	Middle	0.3691	0.8971	0.4625	0.2773	0.2099	1302451	0006647
546	Caliban 3	Phantom (P_3)	3	161	Middle	0.3689	0.8567	0.4793	0.2885	0.2153	1302463	0015504
547	Caliban 3	Phantom (P_3)	3	161	Bottom	0.3696	0.8417	0.4622	0.2834	0.2071	1302472	0013093
548	Caliban 3	Phantom (P_3)	3	161	Bottom	0.3626	0.8641	0.4627	0.2904	0.2147	1302445	0006766
549	Caliban 3	Phantom (P_3)	3	161	Bottom	0.3667	0.8597	0.4620	0.2895	0.2047	1302477	0015452
550	Caliban 3	Stand (S1)	3	149.5	Top	0.3634	0.8577	0.4624	0.2873	0.2148	1302453	0004516
551	Caliban 3	Stand (S1)	3	149.5	Top	0.3545	0.8683	0.4623	0.2894	0.2158	1302467	0013285
552	Caliban 3	Stand (S1)	3	149.5	Top	0.3693	0.8684	0.4625	0.2740	0.1965	1302473	0005670
553	Caliban 3	Stand (S1)	3	140	Middle	0.3674	0.8793	0.4624	0.2831	0.2143	1302438	0014100
554	Caliban 3	Stand (S1)	3	140	Middle	0.3676	0.8679	0.4627	0.2905	0.2161	1302452	0030114
555	Caliban 3	Stand (S1)	3	140	Middle	0.3582	0.8841	0.4820	0.2930	0.2139	1302456	0012200
556	Caliban 3	Stand (S1)	3	95.6	Bottom	0.3494	0.8782	0.4632	0.2920	0.2142	1302464	0005715
557	Caliban 3	Stand (S1)	3	95.6	Bottom	0.3699	0.9056	0.4805	0.2833	0.2109	1302455	0006105
558	Caliban 3	Stand (S1)	3	95.6	Bottom	0.3660	0.8452	0.4796	0.2932	0.2062	1302446	0006481
560	Caliban 3	Phantom 45 Front (P_2)	3	159.6	Middle	0.3641	0.8775	0.4816	0.2916	0.2131	1302459	0008732
561	Caliban 3	Phantom 45 Front (P_2)	3	159.6	Middle	0.3819	0.9008	0.4813	0.2767	0.2132	1302462	0030100
598	Caliban 3	Phantom 45 Front (P_2)	3	159.6	Middle	0.3839	0.8473	0.4624	0.2826	0.2132	1302457	0014541
597	Caliban 3	Phantom 45 Back (P_2)	3	159.6	Middle	0.3576	0.8980	0.4794	0.2727	0.2080	1302448	0006668
599	Caliban 3	Phantom 45 Back (P_2)	3	159.6	Middle	0.3563	0.9035	0.4631	0.2921	0.2133	1302475	0008532
77	Caliban 3	Phantom 45 Back (P_2)	3	159.6	Middle	0.3610	0.8830	0.3460	0.2810	0.1920	1203071	0005595
562	Prospero 2	Phantom (P_5)	3.5	158.5	Top	0.3558	0.8594	0.4815	0.2569	0.2063	1302454	0010200
563	Prospero 2	Phantom (P_5)	3.5	158.5	Top	0.3708	0.8724	0.4625	0.2912	0.2167	1302442	0006664
565	Prospero 2	Phantom (P_5)	3.5	158.5	Top	0.3644	0.8800	0.4799	0.2897	0.2170	1302474	0011210
566	Prospero 2	Phantom (P_5)	3.5	158.5	Bottom	0.3612	0.8364	0.4625	0.2854	0.2156	1302450	0010620

PNAD ID	Irradiation	Location	Distance (m)	Height (cm)	Position	B Covered In Mass (g)	S Mass (g)	Cu Mass (g)	Bare Au Mass (g)	Cd Covered Au Mass (g)	CR-39 TASL #	Panasonic TLD ID
568	Prospero 2	Phantom (P_5)	3.5	158.5	Bottom	0.3728	0.8496	0.4623	0.2863	0.2100	1302461	0010017
570	Prospero 2	Phantom (P_5)	3.5	158.5	Bottom	0.3764	0.8117	0.4630	0.2871	0.2164	1302439	0010711
571	Prospero 2	Stand (S4)	3.5	139.3	Top	0.3677	0.8320	0.4624	0.2829	0.1975	1302449	0011864
577	Prospero 2	Stand (S4)	3.5	139.3	Top	0.3615	0.9098	0.4623	0.2850	0.1959	1302441	0011276
580	Prospero 2	Stand (S4)	3.5	139.3	Top	0.3649	0.8646	0.4817	0.2892	0.2100	1302443	0007602
584	Prospero 2	Stand (S4)	3.5	90.1	Bottom	0.3650	0.8655	0.4619	0.2909	0.2127	1302458	0010362
585	Prospero 2	Stand (S4)	3.5	90.1	Bottom	0.3674	0.8523	0.4632	0.2901	0.2046	1302469	0004643
586	Prospero 2	Stand (S4)	3.5	90.1	Bottom	0.3621	0.8469	0.4628	0.2816	0.2097	1302466	0009971
588	Prospero 2	Phantom 45 Front (P_6)	3.5	161	Middle	0.3651	0.8710	0.4807	0.2708	0.2102	1302465	0011867
589	Prospero 2	Phantom 45 Front (P_6)	3.5	161	Middle	0.3650	0.8950	0.4616	0.2865	0.2137	1302468	0008622
591	Prospero 2	Phantom 45 Front (P_6)	3.5	161	Middle	0.3689	0.8394	0.4630	0.2828	0.2156	1302460	0011561
592	Prospero 2	Phantom 45 Back (P_6)	3.5	161	Middle	0.3623	0.8770	0.4633	0.2908	0.2126	1302470	0005692
594	Prospero 2	Phantom 45 Back (P_6)	3.5	161	Middle	0.3513	0.8517	0.4797	0.2827	0.2132	1302471	0011341

Table B2. Individual PNAD neutron fluence and neutron KERMA results for the CALIBAN irradiation.**Core-facing (0°) Phantom at 3m**

NAD ID #	Neutron Fluence (n cm ⁻²)				Total Neutron KERMA (Gy)	Hp(10) Photon Dose (Sv)	Total Dose (Gy)
	Thermal	1eV - 1MeV	1MeV - 3MeV	> 3MeV			
535	1.86E+10	5.95E+10	1.65E+10	3.74E+09	1.10	0.78	1.88
539	3.86E+09	7.33E+10	1.54E+10	3.75E+09	1.20	0.56	1.76
541	1.66E+10	5.94E+10	1.69E+10	3.47E+09	1.10	0.78	1.88
543	1.69E+10	5.65E+10	1.67E+10	3.68E+09	1.10	0.86	1.96
544	1.82E+10	7.65E+10	1.45E+10	3.75E+09	1.20	0.82	2.02
546	1.59E+10	6.53E+10	1.46E+10	3.66E+09	1.10	0.63	1.73
547	1.52E+10	N.R.	1.29E+10	3.43E+09	N.R.	0.60	N.R.
548	1.88E+10	8.68E+10	1.45E+10	3.67E+09	1.30	0.53	1.83
549	1.48E+10	5.02E+10	1.47E+10	3.59E+09	0.98	0.63	1.61
<i>Average</i>	<i>1.54E+10</i>	<i>6.59E+10</i>	<i>1.52E+10</i>	<i>3.64E+09</i>	<i>1.14</i>	<i>0.69</i>	<i>1.83</i>

N.R. = not reported

Core-facing (0°) Stand at 3m

NAD ID #	Neutron Fluence (n cm ⁻²)				Total Neutron KERMA (Gy)	Hp(10) Photon Dose (Sv)	Total Dose (Gy)
	Thermal	1eV - 1MeV	1MeV - 3MeV	> 3MeV			
550	1.34E+10	5.00E+10	1.38E+10	3.55E+09	0.95	0.54	1.49
551	1.02E+10	6.38E+10	1.49E+10	3.55E+09	1.10	0.33	1.43
552	1.07E+10	8.73E+10	1.60E+10	3.33E+09	1.30	0.53	1.83
553	9.92E+09	7.05E+10	1.48E+10	3.54E+09	1.20	0.34	1.54
554	1.01E+10	8.95E+10	1.62E+10	3.73E+09	1.40	0.51	1.91
555	8.20E+09	7.69E+10	1.46E+10	3.84E+09	1.20	0.47	1.67
556	1.08E+10	5.39E+09	1.51E+10	3.57E+09	0.62	0.48	1.10
557	1.14E+10	4.57E+10	1.66E+10	3.32E+09	0.98	0.39	1.37
558	1.01E+10	5.70E+10	1.29E+10	3.46E+09	0.98	0.52	1.50
<i>Average</i>	<i>1.05E+10</i>	<i>6.07E+10</i>	<i>1.50E+10</i>	<i>3.54E+09</i>	<i>1.08</i>	<i>0.46</i>	<i>1.54</i>

45° Phantom Front at 3m

NAD ID #	Neutron Fluence (n cm ⁻²)				Total Neutron KERMA (Gy)	Hp(10) Photon Dose (Sv)	Total Dose (Gy)
	Thermal	1eV - 1MeV	1MeV - 3MeV	> 3MeV			
560	1.64E+10	6.44E+10	1.13E+10	3.48E+09	1.00	0.69	1.69
561	1.72E+10	6.67E+10	1.49E+10	3.35E+09	1.10	0.76	1.86
598	1.84E+10	6.11E+10	1.53E+10	3.74E+09	1.10	0.60	1.70
<i>Average</i>	<i>1.74E+10</i>	<i>6.41E+10</i>	<i>1.38E+10</i>	<i>3.52E+09</i>	<i>1.07</i>	<i>0.68</i>	<i>1.75</i>

45° Phantom Rear at 3m

NAD ID #	Neutron Fluence (n cm ⁻²)				Total Neutron KERMA (Gy)	Hp(10) Photon Dose (Sv)	Total Dose (Gy)
	Thermal	1eV - 1MeV	1MeV - 3MeV	> 3MeV			
77	1.17E+10	2.72E+10	2.30E+09	3.42E+08	0.31	0.45	0.76
597	1.46E+10	5.59E+10	1.41E+10	2.05E+09	0.95	0.63	1.58
599	1.29E+10	3.66E+10	1.84E+09	4.18E+08	0.38	0.52	0.90
<i>Average</i>	<i>1.31E+10</i>	<i>3.99E+10</i>	<i>6.07E+09</i>	<i>9.38E+08</i>	<i>0.55</i>	<i>0.53</i>	<i>1.08</i>

Table B3. Individual PNAD neutron fluence and neutron KERMA results for the PROSPERO irradiation.

Core-facing (0°) Phantom at 3.5m							
NAD ID #	Neutron Fluence (n cm ⁻²)				Total Neutron KERMA (Gy)	Hp(10) Photon Dose (Sv)	Total Dose (Gy)
	Thermal	1eV - 1MeV	1MeV - 3MeV	> 3MeV			
562	4.02E+09	1.16E+10	1.48E+09	1.42E+08	0.14	0.08	0.22
563	4.88E+09	1.20E+10	1.32E+09	2.35E+08	0.15	0.17	0.32
565	3.63E+09	1.16E+10	1.48E+09	9.78E+07	0.14	0.08	0.22
566	2.20E+09	1.06E+10	9.46E+08	2.46E+08	0.13	0.08	0.21
568	4.51E+09	1.06E+10	1.04E+09	1.22E+08	0.12	0.09	0.21
570	3.58E+09	1.06E+10	9.05E+08	2.39E+08	0.12	0.08	0.20
<i>Average</i>	<i>3.80E+09</i>	<i>1.12E+10</i>	<i>1.19E+09</i>	<i>1.80E+08</i>	<i>0.13</i>	<i>0.10</i>	<i>0.24</i>

Core-facing (0°) Stand at 3.5m							
NAD ID #	Neutron Fluence (n cm ⁻²)				Total Neutron KERMA (Gy)	Hp(10) Photon Dose (Sv)	Total Dose (Gy)
	Thermal	1eV - 1MeV	1MeV - 3MeV	> 3MeV			
571	2.39E+09	9.28E+09	9.88E+08	2.70E+08	0.12	0.05	0.17
577	2.21E+09	9.28E+09	1.08E+09	2.03E+08	0.12	0.06	0.18
580	2.39E+09	8.91E+09	1.10E+09	1.76E+08	0.11	0.05	0.16
584	2.41E+09	1.18E+10	1.39E+09	1.01E+08	0.14	0.05	0.19
585	2.18E+09	1.18E+10	1.22E+09	2.57E+08	0.14	0.07	0.21
586	2.51E+09	1.18E+10	1.18E+09	3.11E+08	0.15	0.05	0.20
<i>Average</i>	<i>2.35E+09</i>	<i>1.05E+10</i>	<i>1.16E+09</i>	<i>2.19E+08</i>	<i>0.13</i>	<i>0.06</i>	<i>0.19</i>

45° Phantom Front at 3.5m							
NAD ID #	Neutron Fluence (n cm ⁻²)				Total Neutron KERMA (Gy)	Hp(10) Photon Dose (Sv)	Total Dose (Gy)
	Thermal	1eV - 1MeV	1MeV - 3MeV	> 3MeV			
588	4.17E+09	1.42E+10	4.20E+08	2.36E+08	0.14	0.08	0.22
589	3.82E+09	1.48E+10	4.39E+08	2.18E+08	0.15	0.17	0.32
591	2.61E+09	1.48E+10	3.80E+08	2.68E+08	0.15	0.07	0.22
<i>Average</i>	<i>3.53E+09</i>	<i>1.46E+10</i>	<i>4.13E+08</i>	<i>2.41E+08</i>	<i>0.15</i>	<i>0.11</i>	<i>0.25</i>

45° Phantom Rear at 3.5m							
NAD ID #	Neutron Fluence (n cm ⁻²)				Total Neutron KERMA (Gy)	Hp(10) Photon Dose (Sv)	Total Dose (Gy)
	Thermal	1eV - 1MeV	1MeV - 3MeV	> 3MeV			
592	2.12E+09	1.25E+10	1.93E+09	7.83E+07	0.16	0.06	0.22
594	2.17E+09	1.21E+10	1.95E+09	1.19E+08	0.16	0.05	0.21
<i>Average</i>	<i>2.14E+09</i>	<i>1.23E+10</i>	<i>1.94E+09</i>	<i>9.87E+07</i>	<i>0.16</i>	<i>0.06</i>	<i>0.22</i>

Table B5. Individual PIC results for both irradiations.

Set #	Model	Exposure Range	S/N	Irradiation	Location	Distance (m)	Height (cm)	Position	Exposure (R)
LLNL-1	730	0-20R	JG215044	Caliban 3	Phantom (P_3)	3	161	Middle	----
	740	0-100R	JG215049	Caliban 3	Phantom (P_3)	3	161	Middle	52
	742	0-200R	JG215057	Caliban 3	Phantom (P_3)	3	161	Middle	60
	746	0-600R	JG215062	Caliban 3	Phantom (P_3)	3	161	Middle	62
LLNL-11	W730	0-20R	ND283807	Caliban 3	Stand (S1)	3	140	Middle	----
	W740	0-100R	ND283809	Caliban 3	Stand (S1)	3	140	Middle	57
	742	0-200R	ND283815	Caliban 3	Stand (S1)	3	140	Middle	54
	746	0-600R	ND283826	Caliban 3	Stand (S1)	3	140	Middle	39
LLNL-12	W730	0-20R	ND283804	Prospero 2	Phantom (P_5)	3.5	158.5	Middle	10
	W740	0-100R	ND283812	Prospero 2	Phantom (P_5)	3.5	158.5	Middle	14
	742	0-200R	ND283821	Prospero 2	Phantom (P_5)	3.5	158.5	Middle	10
	746	0-600R	ND283822	Prospero 2	Phantom (P_5)	3.5	158.5	Middle	30
LLNL-4	W730	0-20R	ND283802	Prospero 2	Stand (S4)	3.5	130	Middle	9
	W740	0-100R	ND283814	Prospero 2	Stand (S4)	3.5	130	Middle	10
	742	0-200R	ND283817	Prospero 2	Stand (S4)	3.5	130	Middle	10
	746	0-600R	ND283823	Prospero 2	Stand (S4)	3.5	130	Middle	20

Table B6. TLD element values for all Panasonic dosimeters used.

NAD #	Irradiation	Location	Panasonic ID	Analysis Path	e1 reading (mR*)	e2 reading (mR*)	e3 reading (mR*)	e4 reading (mR*)	Hp(10) (mrem)	Neutron Dose (mrem)	Included for illustration of proposed changes to analysis algorithms		
											e2/e4	e4 Dose (mrem)	Ratio e2 Dose to e4 Dose
549	Caliban 3	Phantom	0015452	ACC LOW	39326.6	43228.2	2791038	33154.2	63107	518044		30783.8	2.05
547	Caliban 3	Phantom	0013093	ACC LOW	40452.9	40942.8	2856037	31830.9	59770	530388		29555.2	2.02232
546	Caliban 3	Phantom	0015504	ACC LOW	41559.2	43107.2	2864526	34646.9	62930	531683		32169.8	1.95618
548	Caliban 3	Phantom	0006766	ACC HI	49065.2	48334.8	3265660	33782.6	52767	606115		31367.3	1.68223
535	Caliban 3	Phantom	0006247	ACC LOW	50047.1	53487.8	3394774	31734.6	78084	629918		29465.7	2.64999
543	Caliban 3	Phantom	0004079	ACC LOW	53233.8	58862.9	3527618	36096.8	85931	654155		33516.1	2.56388
541	Caliban 3	Phantom	0030242	ACC LOW	53202.1	53710.4	3629652	32656.6	78409	673833		30321.8	2.58589
539	Caliban 3	Phantom	0010280	ACC HI	51674.8	51306.2	3692009	32879.3	56011	685903		30528.6	1.83471
544	Caliban 3	Phantom	0006647	ACC LOW	52661.2	56158.3	3753903	40581.6	81983	696985		37680.2	2.17576
77	Caliban 3	Phantom 45 Back	0005595	ACC LOW	30609.5	31070.7	2154094	20231.7	45359	400043		18785.2	2.41461
599	Caliban 3	Phantom 45 Back	0008532	ACC LOW	33246.1	35653.8	2238496	24254.9	52049	415280		22520.8	2.31115
597	Caliban 3	Phantom 45 Back	0006668	ACC LOW	41486.2	43137.7	2585500	25994.8	62975	479245		24136.3	2.60914
598	Caliban 3	Phantom 45 Front	0014541	ACC LOW	39184.5	41020.9	2826970	32745.1	59884	525010		30404	1.96961
560	Caliban 3	Phantom 45 Front	0008732	ACC LOW	44422.9	47541.1	3142353	27546.4	69403	583425		25577	2.7135
561	Caliban 3	Phantom 45 Front	0030100	ACC LOW	50470.2	52159.9	3450699	36350.2	76146	640479		33751.3	2.25609
551	Caliban 3	Stand	0013285	ACC HI	29319.4	29835.5	1765736	25700.9	32571	327106	1.16087	23863.4	1.36489
553	Caliban 3	Stand	0014100	ACC HI	29279.6	30940.8	1842563	26492.2	33778	2418970	1.16792	24598.1	1.37319
557	Caliban 3	Stand	0006105	ACC HI	37426.8	35652.6	1848564	22525.6	38922	341538	1.58276	20915.1	1.86095
555	Caliban 3	Stand	0012200	ACC LOW	31821	32127.8	1921787	26143.1	46902	2522386	1.22892	24274	1.93219
558	Caliban 3	Stand	0006481	ACC LOW	34157	35537.8	1922206	21637.3	51880	355698	1.64243	20090.3	2.58234
556	Caliban 3	Stand	0005715	ACC LOW	32824	33070.4	2051061	20533.5	48278	380288	1.61056	19065.5	2.53222

NAD #	Irradiation	Location	Panasonic ID	Analysis Path	e1 reading (mR*)	e2 reading (mR*)	e3 reading (mR*)	e4 reading (mR*)	Hp(10) (mrem)	Neutron Dose (mrem)	Included for illustration of proposed changes to analysis algorithms		
											e2/e4	e4 Dose (mrem)	Ratio e2 Dose to e4 Dose
550	Caliban 3	Stand	0004516	ACC LOW	36546.5	36920.7	2123886	23581.4	53899	393324	1.56567	21895.5	2.46165
554	Caliban 3	Stand	0030114	ACC LOW	33917.6	35102.3	2140115	22463	51244	396767	1.56267	20857	2.45692
552	Caliban 3	Stand	0005670	ACC LOW	33911.5	36501.6	2178497	22883.7	53287	403870	1.59509	21247.6	2.5079
565	Prospero 2	Phantom	0011210	NEUTM	8805.9	8850.4	678072	4802.7	8250	126091		4459.33	1.85005
566	Prospero 2	Phantom	0010620	NEUTM	9029.8	8719.1	691488	4445.4	8197	128612		4127.58	1.98591
562	Prospero 2	Phantom	0010200	NEUTM	9193.1	8776.3	709185	4447.3	8285	131924		4129.34	2.00637
570	Prospero 2	Phantom	0010711	NEUTM	8554.5	8633.6	716072	4483.5	7983	133287		4162.95	1.91763
568	Prospero 2	Phantom	0010017	NEUTM	10169	9950.7	858218	5389.6	9378	159786		5004.27	1.874
563	Prospero 2	Phantom	0006664	ACC LOW	10794.2	11694.3	955777	5014.2	17072	177952		4655.71	3.66689
594	Prospero 2	Phantom 45 Back	0011341	NEUTM	5728.2	5675.3	410641	3244	5364	76297		3012.07	1.78083
592	Prospero 2	Phantom 45 Back	0005692	NEUTM	6791.2	7157.3	490104	2911.9	6304	91042		2703.71	2.33161
591	Prospero 2	Phantom 45 Front	0011561	NEUTM	7450.9	7882.8	534037	4401	7226	99180		4086.35	1.76833
588	Prospero 2	Phantom 45 Front	0011867	NEUTM	8592.1	8516.3	706579	4536.7	7964	131506		4212.35	1.89063
589	Prospero 2	Phantom 45 Front	0008622	ACC LOW	10975.1	11389.7	829248	5112	16627	154145		4746.52	3.50299
577	Prospero 2	Stand	0011276	NEUTM	6261.1	6120.2	402147	3145.6	5732	74616	1.94564	2920.71	1.96254
580	Prospero 2	Stand	0007602	NEUTM	5699.4	5843.7	434832	3063.2	5376	80841	1.90771	2844.2	1.89016
571	Prospero 2	Stand	0011864	NEUTB	5185.6	5218.2	456496	3017.9	4907	602251	1.72908	2802.14	1.75116
584	Prospero 2	Stand	0010362	NEUTM	5832.4	5735.1	457064	3060.4	5383	85024	1.87397	2841.6	1.89436
585	Prospero 2	Stand	0004643	NEUTM	7198.6	7418.4	473421	3058.9	6608	87843	2.42519	2840.2	2.32659
586	Prospero 2	Stand	0009971	NEUTM	5632	5731.1	477305	3055	5301	88851	1.87597	2836.58	1.8688